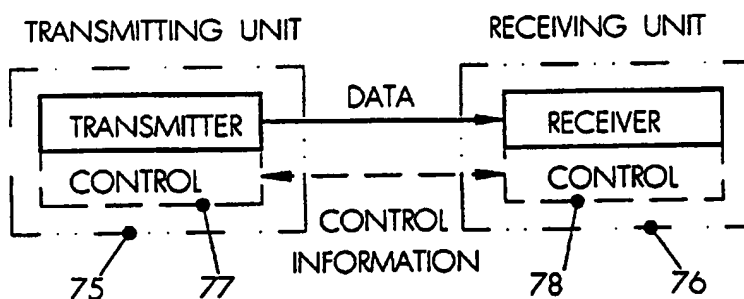




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(54) Title: WIRELESS OPTICAL COMMUNICATION SYSTEM WITH ADAPTIVE DATA RATES AND/OR ADAPTIVE LEVELS OF OPTICAL POWER



(57) Abstract

The wireless optical (in particular infrared) communication system with at least one transmitter (75) and one receiver (76) comprises control means (77, 78), which dynamically adapt the data rate and/or the optical power of the transmitter in dependence of signal-to-noise ratio of the receiver. Due to this adjustment, optimized system performance is maintained even under the influence of ambient light which statistically changes the signal-to-noise ratio of the receiver. The best compromise between data rate, bit error rate and transmission range is dynamically determined. The control function is distributed between transmitting and receiving system unit. The control information is communicated via wireless optical communication.

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DESCRIPTION

**Wireless optical communication system with adaptive data rates
and/or adaptive levels of optical power**

5

TECHNICAL FIELD

10 The present invention relates to a wireless optical communication system for data transmission.

BACKGROUND OF THE INVENTION

15 With the rapidly increasing number of workstations and personal computers (e.g. desktop or handheld ones) in all areas of business, administration, fabrication etc., there is also an increasing demand for flexible and simple interconnection of these systems. There is a similar need as far as the hook-up and interconnection of peripheral devices, such as keyboards,
20 computer mice, printers, plotters, scanners, displays etc., is concerned. The use of electrical interconnects becomes a problem with increasing number of systems communicating with each other, and in many cases in which the location of systems, or the configuration of subsystems, must be changed frequently. It is therefore desirable to gain flexibility and thus to eliminate
25 electrical interconnects for such systems and to use wireless communication instead.

The use of optical signals for wireless transfer of digital data between systems and devices has received increased interest during recent years
30 and has lead to applications in commercial products. One example is the optical remote control of electronic instruments. Another example is the communication between information systems in an office environment. Digital data to be transferred between a transmitting system and a receiving

1 system are transformed to modulated optical signals which are radiated
from a light source - in particular an infrared (IR) one - at the location of
the transmitting system and are received and converted to electrical
signals and then to digital data by the receiving system. The optical signals
5 might directly propagate to the optical receiver of the receiving system or
they might indirectly reach the receivers after changes of the direction of
propagation due to processes like reflections or scattering at surfaces.
Today, the former case is realized in docking stations for portable
computers where the data transfer takes place between an optical
10 transmitter and a receiver which are close together at a distance on the
scale of cm and properly aligned. The latter case is typical for applications
in an office environment in which undisturbed direct transmission of optical
signals between transmitters and receivers several meters away from each
other is unpractical or even impossible due to unavoidable perturbations of
15 the direct path. One known approach to achieve a high degree of flexibility
is to radiate optical signals from the transmitting system to the ceiling of an
office where they are reflected or diffusely scattered. Thus, the radiation is
distributed over a certain zone in the surroundings of the transmitter. The
distribution of the light signals spreading from the ceiling depends on many
20 details which are characteristic for the particular environment under
consideration. However, essential in this context is mainly that the
transmission range, i. e. the distance between transmitting system and
receiving system, is limited to some final value, hereafter called the
transmission range, since the energy flux of the transmitted radiation
25 decreases with increasing distance of propagation and the receiver
sensitivity is limited due to a final signal-to-noise ratio. Typical known
systems, operating at levels of optical power which are limited by the
performance of the light sources and safety requirements for light exposure,
have demonstrated transmission ranges of several meters for data rates of
30 1 Mbps.

The latter example illustrates basic features of wireless optical
communication and indicates fields of applications where it is favorably

1 applied in contrast to another competitive method of wireless
communication, the radio frequency (RF) transmission. Wireless optical
communication allows data transmission which is short range, whereas RF
transmission is potentially long range. Furthermore optical wireless
5 communication in an office environment is localized since typical
boundaries of an office such as walls and ceilings are not transparent for
light but for RF waves. That is why possible interferences between different
communication systems are easier to control and a simpler way for
achieving data security is possible for a wireless communication system
10 which is based on optical radiation rather than RF transmission. RF
transmission is even restricted by communications regulations and licenses
whereas optical wireless communication systems are not.

Crucial parameters of a wireless optical communication system are the
15 achievable data rate and the distance between the systems exchanging
data. In an office environment, it can be necessary to communicate data
over distances exceeding the transmission range of a single optical
transmitter. However, the transmission range of a single optical transmitter
can be extended within the concept of wireless communication, for example
20 by introducing optical repeaters. One example of such an extended system
has been proposed in US patent 4 402 090 entitled "Communication System
in which Data are Transferred Between Terminal Stations and Satellite
Stations by Infrared Systems". In this patent, a system is described which
provides a plurality of satellite stations, i. e. stations usually fixed at the
25 ceiling of a large room. Terminals can optically interact with satellites within
their transmission range, and data can be distributed via intersatellite
communication thus enabling the distribution of data over distances beyond
the transmission range of a single transmitter.

30 When designing a wireless optical communication system, one has to be
aware of unavoidable ambient light, such as daylight or light from lamps,
which always reaches the optical detectors, unless the system is restricted
for the use in a completely dark environment. Unavoidable ambient light can

1 lead to time-dependent signals, for example AC signals from lamps, and is
an important, in many practical cases the dominant source of noise in the
optical receiver. Thus, ambient light influences the signal-to-noise ratio of
the receiver and, therefore, affects the transmission range. The appearance
5 of unavoidable light is mostly statistical and often difficult to control and its
intensity can drastically change, as it is apparent for sunlight or lamps being
switched on/off. A further realistic effect which statistically affects the
signal-to-noise ratio and thus the transmission range is the occurrence of
optical path obstructions influencing the receiver signal. In an office
10 environment for example, moving users can change the strength of the
transmitted signals and the influence of unavoidable ambient light as well.

In present wireless communication systems, first obvious attempts have
been made to handle the ambient-light problem. Usually, low frequency
15 (≤ 500 KHz) AC signals, which can be attributed to common room
illumination, are suppressed with electrical filters after the conversion of
light to electrical signals. Optical filters are used to restrict the spectrum of
undesired ambient light. However, a significant portion of daylight is
spectrally in the same range as the optical radiation of the light sources
20 appropriate for wireless communication systems.

Present optical wireless communications systems which are designed for
applications in the presence of ambient light work with fixed data rates and
fixed values of optical power. No case study is known which gives an
25 analysis of how the trade-off between data rate and distance between the
transmitting and the receiving part of the system is influenced by ambient
light in a variety of situations representative for an office environment.
Since these trade-offs have not yet been studied for such systems, the
benefit of control and optimization schemes which allow the dynamic
30 optimization of wireless optical communication systems exposed to
changing levels of ambient light with respect to transmission rate,
transmission range and transmission security (bit error rate) has not been
recognized. Therefore, no attempt has been made to introduce such control

1 and optimization schemes. Today's systems, which operate at a fixed
transmission rate, offer the desired degree of data security only at the
expense of a reduction of the transmission range which corresponds to
security margins taking the influence of ambient light into account. For
5 today's systems, these security margins must be determined in
trial-and-error experiments, individually for each particular configuration in
each particular environment. Systems offering automatic control and
optimization of performance in the presence of ambient light are not known.

10

SUMMARY OF THE INVENTION

It is an object of this invention to provide a wireless optical communication
system which comprises at least one transmitting and one receiving unit for
15 optical signals and is suited for operation under the condition that the
optical receiver is exposed to unavoidable ambient light, which deteriorates
the receiver sensitivity. It is assumed that the exposure might statistically
change with time.

20 It is another object of this invention to provide a method and an apparatus
for optimizing the system performance under consideration of dynamically
changing exposures to ambient light.

The invention as claimed is intended to meet these objectives. It provides a
25 method and an apparatus for improved wireless optical communication. The
improvement is achieved by introducing the optical power of the
transmitting unit and/or the data rate as adaptable parameters, thus offering
a useful extra degree of freedom and more flexibility in the design of
wireless optical communication systems. Furthermore, the optical power of
30 a transmitting system and the data rate are parameters which can be set
under automatic control. Such control can be achieved with many different
means. A few examples of such control means are cited in claims 1 to 12
and in the description of the invention. In addition, said parameters can be

1 adapted automatically if required. This application is adequate for systems
which are exposed to fluctuating ambient light. For example, taking the bit
error rate as the main criterion, the data rate can always be dynamically
adapted to its momentary upper limit depending on the exposure to ambient
5 light.

In conclusion, this invention provides a method and an apparatus for
improved wireless optical communication. The improvement is achieved by
introducing automatic control means for the optical power of a transmitting
10 unit and/or the data rate.

Advantages achievable with this invention are:

- enhanced flexibility in system design;
- 15 • simplification of integration of systems operating with different data
rates;
- dynamical performance optimization;
- 20 • controlled bit error rates and thus data security even for adverse
exposure to ambient light.

25

30

DESCRIPTION OF THE DRAWINGS
AND NOTATIONS USED

The invention is described in detail below with reference to the following drawings:

FIG. 1A shows a wireless IR link between a computer and a keyboard.

FIG. 1B shows a wireless IR network, sometimes called LAN on a table, interconnecting different computers and terminals as well as peripheral devices (e.g. a printer).

FIG. 1C shows a wireless IR network with ring topology, called Intra Office LAN, interconnecting different computers and a mainframe.

FIG. 1D shows part of a wireless IR network with a repeater situated at the ceiling, called Intra Office LAN with repeater, usually employed in open area offices, conference rooms, or factory halls.

FIG. 2 shows three configurations of a transmitter/receiver pair considered as model systems for wireless optical intraoffice communication.

FIG. 3 illustrates the received optical power plotted against the distance S between a transmitter and receiver, for the three different transmitter/receiver configurations illustrated in Figure 2.

FIG. 4 illustrates some examples of the bit error probability P_e versus distance S between receiver and transmitter.

- 1 **FIG. 5** illustrates estimated relative data throughput T_o versus distance S , for a vertical transmitter/receiver configuration, using different improvement schemes.
- 5 **FIG. 6** illustrates the attainable transmission ranges for four different data rates (0.01 Mbps - 10 Mbps).
- 10 **FIG. 7** depicts block diagrams for different architectures of wireless optical communication systems comprising a transmitter/receiver pair and control means for optical power and/or data rate.
- 15 **FIG. 8** shows an implementation of an optical receiver suited for the adaptation of the data rate. As an example a special design for signals which are encoded by pulse position modulation (PPM) is shown.

GENERAL DESCRIPTION

20 In general, a system for wireless optical communication comprises at least one unit serving as transmitter and a second one serving as receiver, the transmitter comprising a light source, such as a light emitting diode (LED) or a laser diode, and the receiver comprising a photodiode. The word unit

25 is hereinafter used as a synonym for all kinds of computers, terminals, repeaters, peripheral devices etc., which might communicate with each other, either unidirectional or bidirectional. Normally, infrared (IR) light is used for wireless optical communication. That is why the term 'IR communication' is used in the following, although the results presented

30 in the following are not restricted to a specific range of the light spectrum.

Figure 1 shows four examples for applications of wireless optical communication in an office environment, one basic transmitter/receiver

1 configuration for direct IR communication and three configurations for indirect IR communication.

Direct transmitter/receiver coupling is well suited for applications where
5 only two, or just a few, units use the same IR channel. An example is illustrated in Figure 1A. In this Figure, a first unit, for example a keyboard 21, is coupled to a second unit, a computer 20. This kind of wireless IR link might be unidirectional and the maximum distance is usually less than 1 meter. The direct line-of-sight path between these two units has to be
10 obstruction-free to facilitate reliable operation.

A wireless IR network, sometimes called LAN on a table, is illustrated in Figure 1B. As shown in this Figure, three different units are linked to a fourth one. In the present example, two computers 23 and 25 and a terminal
15 24 are linked to a printer 22. Direct as well as indirect configurations are suitable for these kind of applications.

In Figure 1C, a wireless IR network with ring topology, called Intra Office LAN is shown. This IR network interconnects three computers 27 with a
20 mainframe machine 26. Usually indirect configurations are better suited for Intra Office IR networks.

Another exemplary IR network configuration is shown in Figure 1D. A first unit, e.g. a repeater 28, is situated at the ceiling in order to be able to
25 communicate with remote units. In the present example the remote units are computers 29. Such a configuration is usually called Intra Office LAN with repeater, and might be employed in open area offices, conference rooms, and factory halls.

30 In the following an evaluation of the performance limits of wireless optical communication systems is presented. For the sake of simplicity three different configurations of a single transmitter/receiver pair are considered, a vertical transmitter/receiver configuration, a tilted transmitter/receiver

1 configuration and a spotlight transmitter/receiver configuration (see
Figure 2). As the following analyses show, these three examples have
similar performance characteristics which differ only slightly. Thus these
examples are considered as representative models. As measures of their
5 performance, the data rate, the bit error rate and the distance between
transmitter and receiver are taken. In a first step, the trade-offs between
these parameters are derived from analyses of the signal-to-noise ratio and
a calculation of the probability for the occurrence of a bit error (bit error
rate). In a second step, the influence of ambient light is included. On this
10 basis optimization schemes are discussed.

The formulae given in the following sections provide a reasonable
approximation of the power received at the photodiode as a function of the
distance between the transmitter 10 and the receiver 11. It is assumed that
15 the transmitter emits a narrow parallel beam which is reflected at the ceiling
or a similar surface as a diffuse (Lambertian) point source. The signal power
incident on the photodiode is then given as the radiation contained in the
solid angle bounded by the projected photodiode area. It is assumed that
the path of the propagating light is not obstructed. The following
20 parameters are used:

$P_s = 1 \text{ Watt}$	average optical power of the transmitter
$A_r = 1 \text{ cm}^2$	photodiode area
25 $H = 1.8 \text{ m}$	height of ceiling above desk top
$\rho = 0.7$	reflection coefficient of ceiling
30 $S = 0 - 20 \text{ m}$	distance between transmitter and receiver

1 Vertical transmitter/receiver configuration:

This first indirect configuration, illustrated in Figure 2A, is characterized in that the LED of the transmitter and the photodiode of the receiver point
 5 upward and normal to the ceiling of a room. This configuration does not need alignment of the transmitter and receiver, but produces a 4th-power signal attenuation with distance S , S being the distance between the transmitter and the receiver. The received signal power is approximately given by

10

$$P_r = \rho P_s \frac{A_r}{R^2 \pi} \cos^2 \gamma = \rho P_s A_r \frac{H^2}{\pi (H^2 + S^2)^2} \quad (1)$$

15 It has been experimentally found that formula (1) underestimates the power levels with increasing distance S . An approximate correction can be made by multiplying equation (1) with a correction factor. This correction is necessary since multiple reflections have not been taken into account.

20 Tilted transmitter/receiver configuration:

This configuration (see Figure 2B) requires that the LEDs of all transmitters and the photodiodes of the receivers are approximately directed towards the center of the ceiling of the room. In practice, it suffices that remote
 25 transmitters and receivers located at the periphery of the transmission range are tilted by approximately 45° and face the office interior, whereas other transmitters and receivers located at the center are pointing upward. The advantages of the tilted configuration are:

- 30 1. The signal power is spread more uniformly thus allowing a greater transmission range.
2. In most cases, direct exposure to sunlight or desk lamps can be avoided.

1 3. Transmitters and/or receivers located at the periphery can in many cases benefit from a direct line-of-sight path thus increasing the power efficiency.

5 However, this approach requires a flexible integration of the transmitter and receiver into the unit's housing. In case of a tilted configuration the received signal power is approximated by the expression

$$10 \quad P_r = \rho P_s A_r \frac{H}{\{H^2 + [S - H(1 - e^{-S/H})]^2\}^{\frac{3}{2}}} \quad (2)$$

Spotlight transmitter/receiver configuration:

15 This particular configuration is characterized in that, in addition to the common alignment of all transmitters and receivers, a collimated narrow LED beam is required, allowing the reflected spot to appear at the intersection of the LED axis with the ceiling. The reflected diffuse point source therefore appears halfway between the most distant
20 transmitter/receiver pair, resulting in the smallest propagation loss. The corresponding expression for the received signal power P_r is then

$$25 \quad P_r = \rho P_s \frac{A_r}{R^2 \pi} \cos \gamma = \rho P_s A_r \frac{8 H}{\pi (4 H^2 + S^2)^{\frac{3}{2}}} \quad (3)$$

Since LEDs with small beam angles are neither easily produced nor commercially available, other light sources with small half-power angles are required. A collimated laser source, for example, could satisfy the above
30 conditions. The resulting narrow field-of-view would also allow the use of large aperture lenses with considerable optical gain, as well as narrow optical bandpass filters to suppress the undesired ambient light outside the spectrum of the optical signal source. It is a disadvantage of this concept

1 that the complicated alignment procedure is not suited for user-friendly mobile applications. Note that, when herein referring to optical signal sources, all different kinds of diodes, including the conventional LEDs as well as laser diodes, are meant.

5

In Figure 3, the received optical power P_r is plotted against distance S for the three basic indirect transmitter/receiver configurations addressed above. The diagram in Figure 3 is based on the assumption that the source power $P_s = 1$ W and the photodiode area $A_r = 1$ cm². In addition, the transmitter is assumed to be located at the position $S = 0$, whereas the receiver is moved a distance S .

From Equations (1) - (3) the receiver signals can be obtained for each configuration. In the following these results are related to the receiver noise and subsequently converted to the bit error probability P_e as a function of distance S . At this point the influence of the ambient light environment can be taken into account as contribution to the shot noise of the receiver.

A simple model is assumed that estimates the bit error probability P_e as a function of the distance S and the shot noise generated by different ambient light environments. The following parameters are used in addition to the Boltzmann constant k , the absolute temperature T , and the electron charge e :

25 $\eta = 0.5$ A/W photodiode efficiency

$R_1 = 1$ k Ω photodiode bias resistor

The mean square noise current is given by

30

$$\overline{i_n^2} = \frac{4 k T B}{R_1} + 2 e I_b B \quad (4)$$

1 where B is the electrical bandwidth of the receiver, and I_b the photodiode
 bias current due to imperfect optical filtering of the ambient light. The first
 noise term represents a thermal noise floor (preamplifier noise assumed
 included) which is present at all times. Note that due to the assumed low
 5 $1\text{ k}\Omega$ value (to prevent excessive photodiode bias voltages) the noise floor is
 rather high. In practice, lower noise levels can be realized, resulting in
 improved transmission distances for fluorescent environments. The shot
 noise term depends on the ambient light level passing an optical filter
 situated in front of the receiving photodiode. Different kinds of optical
 10 filters, if any, such as optical interference filters or absorption filters, might
 be used.

We assume the transmission of a binary data stream consisting of a
 sequence of symbols, either "0" or "1", each symbol denoting one bit of
 15 information, the "1" being represented by a single optical pulse of duration
 T_p and the "0" being represented by the lack of a signal during the time span
 T_p . For this particular coding scheme, the time per transmitted bit, T_b , is
 equal to T_p , and the data rate of the transmission generally defined as bit
 rate $R_b = 1/T_b$, i. e. the momentary speed at which the bits of information are
 20 transmitted and recognized as "0" or "1" by the receiver, is equal to $R_b = 1/T_p$.

In order to assure that the receiver transmits a single pulse without
 significant distortion but suppresses noise as good as possible, we assume
 the relation

25

$$B \simeq \frac{1}{T_b} = R_b \quad (5)$$

30

for the bandwidth B of the receiver. The mean signal current is related to
 the received signal power P_r through

$$\bar{I}_s = P_r \eta \quad (6)$$

1 and the signal-to-noise (S/N) ratio is defined by

$$\alpha = \frac{\bar{i}_s}{\bar{i}_n} \quad (7)$$

5

The bit error probability for binary transmission and white Gaussian noise is given by the error function which is herein approximated with

10

$$P_e \leq \frac{1}{2} e^{-\frac{\alpha^2}{2}} \quad (8)$$

to gain a simple analytical expression which, however, overestimates the bit error probability. In Figure 4 some examples of the bit error rate P_e versus distance S are shown which illustrate the existence of a well defined communication cutoff distance for a given ambient light environment. Figure 4 holds for the data rate $R_b = 1$ Mbps. As ambient light environment, exposure by full sunlight (full lines) and light of fluorescent lamps (dashed-dotted lines) has been chosen.

20

The probability of at most m errors occurring in a data packet containing n bits (assuming independent bit errors) is given by the cumulative binominal distribution

25

$$p_m = \sum_{j=0}^m \binom{n}{j} P_e^j (1 - P_e)^{n-j} \quad (9)$$

30

To estimate the data throughput, i. e. the average speed of the transmission of data excluding overhead such as address information, idle bits etc., we assume a "Stop and Wait Automatic Repeat Request (ARQ)" transmission procedure. With $m = 0$ (zero errors occurring in the packet) the relative

1 data throughput, which is normalized with respect to the maximum data rate
 R_{\max} , a design parameter of the system, is given by

$$5 \quad T_o = \frac{R_b}{R_{\max}} (1 - P_e)^n \frac{d}{n + p + i} \quad (10)$$

We wish to analyze Equation (10) for the parameters

10 $R_{\max} = 10 \text{ Mbps or } 1 \text{ Mbps}$

$R_b = 10 \text{ Mbps, } 1 \text{ Mbps, } 0.1 \text{ Mbps, } 0.01 \text{ Mbps}$

$d = 1024$ number of data bits per packet

15 $n = 1064$ number of total bits per packet, including addresses
 and CRC (cyclic redundancy check)

$p = 16$ number of preamble bits in a packet

20 $i = 72$ number of idle bit intervals between packets

For this particular example, the maximum throughput (at $R_b = R_{\max}$) is 0.889
 due to the assumed ratio of payload to overhead.

25 The estimated data throughputs T_o versus distance S for vertical
 transmitter/receiver alignment using the following four known exemplary
 improvement schemes are illustrated in Figure 5. As an example the data
 rate $R_b = R_{\max} = 1 \text{ Mbps}$ has been considered.

- 30 • Optical absorption filter (standard version):
 The transmission limit in direct sunlight is given by the filled area in
 Figure 5 and amounts to only 2.5 to 3 meters. A similar limit has been
 verified with measurements of conventional IR systems. The range in a

1 fluorescent light environment is indicated by the thin solid line
 ($\simeq 7$ m).

- Optical interference (IF) filter with optical bandwidth corresponding to
5 the width of a typical LED emission spectrum ($\delta\lambda \simeq 50\text{nm}$) :

 The range improvement is shown with the heavy and thin dashed lines
 for direct sunlight and fluorescent light, respectively. The improvement
 is about 0.5 meters for direct sunlight. Since fluorescent light contains
 only little IR-radiation, nearly no improvement can be gained in this
10 case.

- Error correction encoding:

 The use of an error correction code allows a limited number of
 corrupted bits to be restored which is equivalent to allowing a smaller
15 signal level for a given noise level (coding gain). This gain might be
 used to improve the transmission range somewhat. For a commercially
 available Reed-Solomon Encoder/Decoder chip set a coding gain of
 3 dB was assumed. The combined effect of the IF-filter and the coding
 gain is shown with the dashed-dotted lines providing a range
20 improvement of $\simeq 1$ meter.

- Variable packet sizes:

 Transmitting very short packets improves the probability of receiving
 uncorrupted messages for a given bit error probability. However, as
25 found by carrying out different measurements, the range improvement
 is negligible.

 In Figure 6 the attainable transmission ranges for a tilted
 transmitter/receiver configuration are estimated for four different data rates
30 (0.01 Mbps - 10 Mbps). With 0.1 Mbps a transmission range of up to 10
 meters can be achieved with the transmitters and receivers exposed to
 direct sunlight, as illustrated in Figure 6. The open and full circles in Figure
 6 represent experimental values.

1 From Figure 5 and Figure 6, general design criteria for wireless optical
communication systems which operate with optimized performance in an
ambient light environment can be deduced. The transmission range of a
system working with 10 Mbps is limited to roughly 2 m if typical extreme
5 cases for exposures to ambient light are considered. On the other hand,
perfect (error free) transmission over 'long' distances ($\approx 10\text{m}$) requires an
extremely low data rate (10kbps). Therefore, practical applications of
wireless optical communication systems are rather limited if they are
operated at a fixed data rate. Such systems are either fast and short-range
10 or slow and long-range. However, today's applications require more design
flexibility. Unfortunately, the conventional improvement schemes mentioned
above can only compensate a negligible portion of the effect which can be
attributed to ambient light.

15 In accordance with this invention, the desired gain in design flexibility can
be achieved by using the data rate and the optical power of the transmitter
as adaptable parameters and introducing control means for their control.
Automation of this control procedure allows for dynamic optimization in the
sense that the best compromise between data rate and transmission range
20 can always be found for a predefined bit error rate.

The control of the optical power and the data rate are related to the control
of the signal-to-noise ratio of the receiver. The optical power of the
transmitter influences the signal of the receiver. However, the maximum
25 data rate corresponds to the smallest signal-to-noise ratio which is
compatible with a predefined bit error rate and, therefore, to the signal
bandwidth of the receiver. Therefore, a method which changes the data rate
corresponds to a method which changes the suppression of noise with
respect to the signal.

30

Methods influencing optical power and/or data rates are known. The power
of the light source of the transmitter can be influenced by the drive current
which can be automatically controlled by means which are state of the art.

1 Alternatively, light modulators could be used. Examples for such devices
are electrooptic modulators, based on electroabsorption or electrorefraction.
From the signal-to-noise point of view, it is favorable to operate the light
source at the highest power level which is limited by the device
5 performance and safety requirements. The data rate is basically defined by
the chosen coding scheme and the time per pulse T_p . The control of the data
rate has two aspects, namely, how to influence the data rate and how to
communicate the information about the proper data rate between transmitter
and receiver, i.e. how to synchronize transmitter and receiver. As far as
10 methods affecting the data rate are concerned, a change of T_p relates to a
modification of the electrical bandwidth B of the receiver and thus to a
change of the receiver's noise. B can be controlled with an adjustable
electrical filter. Such devices are known. One example of how to influence
the data rate via a particular coding scheme even for a constant time per bit
15 T_b and a constant time per pulse T_p is the multiple transmission of redundant
information. In this case individual symbols of the code, each related to a
time frame of a given duration T_2 and each representing a certain number of
bits, are transmitted m times, m being an integer. This multiple
transmission reduces the data rate by $1/m$, but enables the application of
20 noise suppression procedures such as signal averaging, leading to an
improvement of the signal-to-noise ratio of the receiver by roughly a factor
 $1/\sqrt{m}$, even if the electrical bandwidth of the receiver is left unchanged.
This example and additional concepts for the adjustment of data rates are
discussed below in the context with an embodiment in accordance with this
25 invention. A realization of the transmitter/receiver synchronization is also
given there.

The block diagrams in Figure 7 show how such control processes could be
organized in general. A control system might act as an independent system
30 72 which interacts with the transmitter 70 and the receiver 71 for setting
data rate and/or optical power (Figure 7A). Input parameters for the control
system might be a measure for the signal-to-noise-ratio of the receiver 71 or
signals from detectors which characterize the ambient light. In accordance

1 with this invention the information between the control system 72 and
transmitter 70 and receiver 71 could be transferred via wireless optical
communication. In this case the receiver must comprise an additional
optical transmitter and the transmitter has to comprise an additional optical
5 receiver. Another realization of the same inventive concept is the
integration of the control function (77, 78) into the transmitting unit and the
receiving unit itself (Figure 7B). The transmitting and the receiving unit can
exchange all information about data rate and/or optical power in a hand
shake process. Again, wireless optical communication is an adequate
10 method for this procedure in accordance with this invention.

In the following, a receiver which is in accordance with the present
invention is described. The receiver is illustrated in Figure 8. An example
for the synchronization of transmitter and receiver is also given below.

15

As data encoding scheme, Pulse Position Modulation (PPM) is assumed, i.e.
the data stream is split up into a sequence of packets. Each packet defines a
sequence of time frames of duration T_2 . By definition, n bits are represented
by m equivalent pulses each of them being related to one of m subsequent
20 time frames, having the duration $T_p = T_2/2^n$ and being identified by one of 2^n
possible equidistant positions within each time frame. This particular
definition of PPM-encoding includes the possibility of repeating the same
information, encoded by the position of a single pulse with respect to one
time frame, m times. Thus, in the general case $m \geq 1$ the data rate, i. e.
25 the number of transmitted bits per time of transmission, is given by

$$R_b = \frac{n}{mT_2} \quad (11)$$

30

A reasonable compromise between the requirement of transmitting pulses
without significant distortion and suppressing noise as much as possible is
found for setting the receiver bandwidth $B \approx 1/T_p$.

1 In this type of encoding, the possibilities for changing the data rate are at
least threefold. On the one hand, the number n of bits per time frame and
thus T_2 can be changed in combination with the optical output power of the
transmitter. However, in many cases the application of this approach is
5 limited due to power efficiency considerations. Often it is desired to
achieve the highest signal possible. In this case, it is useful to operate the
light source of the transmitting unit at the highest power levels which are
compatible with safety restrictions and the limits of the device performance.
Usually upper limits for the average and the peak of the optical power must
10 be defined. Therefore, also the number n of bits related to a single time
frame has an upper limit. Performance data of typical known LEDs suggest
to choose $n = 4$ and $T_p \approx 250\text{ns}$ for a transmission with the data rate
1 Mbps. A second approach is affecting the noise level by changing the
receiver's bandwidth B in combination with the pulse duration T_p according
15 to the relation given above. Third, if B and T_p are fixed, the transmission of
each time frame can be repeated m times within a single packet, thus
reducing the data rate by $1/m$ with respect to the case $m = 1$. Digital
signal processing of the received m equal frames, as described later, will
decrease the bit error rate.

20

The receiver illustrated in Figure 8 comprises an opto-electronic receiver
with photodiode 34. The received optical signal is converted to an electrical
signal which is fed to the amplifier 35. An optional gain control circuit 45
(AGC) might be employed in order to keep the amplitudes at the output of
25 the amplifier 35 constant. A bandpass filter 46 provides a bandpass-filtered
signal (with bandwidth $\sim B$) which is fed to a slicer 47. Means 48 for
baseline restoration are provided to extract the baseline signal from the
signal at the output of amplifier 35. This baseline signal forwarded from the
means 48 for baseline restoration to said slicer 47 is not constant due to ac
30 coupling. Hard decisions on detected pulses (true pulses or noise) are
clocked into a shift register 50. The shift register 50 has 2^n cells in order to
contain one frame length. The clock signal ϕ_p for triggering said register 50
is generated using means 49 for preamble processing. For enabling

1 transmitter/receiver synchronization and proper processing of received
data, a sequence of preamble bits, which carries signals for the
synchronization of the system clock and for the synchronization of the time
frame T_2 and delivers encoded information about the data rate (i.e. n and
5 m), is transmitted at the beginning of each data packet. The preamble
processor 49 provides signals for clock extraction 59.1, frame
synchronization 59.2, data rate detection 59.2, and carrier sensing 59.3. The
means 49 for preamble processing are assumed to deliver clock pulses ϕ_P
starting at the beginning of the first frame of the preamble .

10

The shift register 50 provides 2^n output signals forwarded to counters (flip
flops) 54.1 through 54.x. With no errors, only one counter will contain the
detected pulse in the correct position. With errors, several counters may
contain a "pulse". At the end of each frame, the output of the shift register
15 50 are clocked into said counters 54.1 - 54.x., triggered by a counter clock
 ϕ_F obtained from a first divider 51. This first divider 51 divides the clock
pulse ϕ_P by 2^n .

In case of transmission at highest speed, i.e. with $m=1$, all frames are only
20 transmitted once. The contents of the counters 54.1 - 54.x are then
transferred to means 55 for bit position estimation with a clock ϕ_{MF} . The bit
position estimator 55 makes an attempt to relate a detected pulse to its
position with respect to its corresponding time frame T_2 . The clock ϕ_{MF} is
equal to ϕ_F except a phase shift. After having the contents of the counter
25 transferred to the bit position estimator 55, the counters are reset by a
signal provided at an output of a second divider 52. If no error occurred,
only one counter contains the pulse count "1" and all others "0". In other
words, the bit position estimator delivers a measure of the signal-to-noise
ratio of the receiver and, equivalently, the bit error rate. From the results of
30 the bit position estimation, the transmitted data are extracted by the
decoder 56, and serialized by means 57 which receives trigger signals from
means 53. The interface logic 58 makes the received data available for
subsequent data processing.

1 In case of repeated transmission, e.g. with $m=10$, 100, or 1000, with each
clock ϕ_F the counters are incremented by the contents of the shift register
50. Here the clock signal provided by said second divider 52 is $\phi_{MF} = \phi_F/m$,
i.e. this divider divides the clock signal by m . After m frames, the contents
5 of the counters are transferred to said means 55 for bit position estimation.
Then, the counters are reset by a trigger signal 59.4 generated by divider
52. In this way, the counters perform signal averaging of 2^n samples of the
optical signal received during one time frame T_2 . Thus, they deliver a
sampled signal whose signal-to-noise ratio is improved by a factor $1/\sqrt{m}$.

10

For adapting the data rate by electrical filtering, the adjustment of the width
of the bandpass filter of the receiver is required. For this purpose,
adjustable analog or digital filters are needed. The pulse lengths are much
longer at low data rates such that the power of the transmitter's light source
15 (e.g. a LED) must be reduced to prevent overheating. It is a disadvantage of
this method that data rates below about 500kHz are not possible. This part
of the frequency spectrum must be completely suppressed to eliminate the
dominant noise contribution due to fluorescent lamps.

20 According to this invention, the receiver described above can be used in a
wireless optical communication system with adaptive data rates in the
following way. PPM encoding is chosen. It is assumed that the parameters
 m and n , i.e. the number of repetitions of each time frame and the number of
bits per time frame, respectively, are taken as control parameters for the
25 data rate in addition to the optical power of the transmitter. As mentioned
above, all information about clock and frame synchronization and the data
rate are contained in the sequence of preamble bits of each data packet.
Furthermore, synchronization of clock and frame and proper data
processing in accordance with predefined values for m and n is controlled
30 by the preamble processor 49. Starting from these prescriptions, a control
means in accordance with this invention is described. As an example, the
system architecture shown in Figure 7B is used, i. e. the control function is
distributed between the transmitter and the receiver. For the exchange of

1 control data, wireless optical communication is used, i. e. the transmitting
unit of the system comprises a receiver as shown in Figure 8, and the
receiving unit of the system comprises an optical transmitter which might be
of the same type as the one in the transmitting unit of system. Since all
5 information related to the synchronization of the transmitting and receiving
system units is included in the communication protocol, namely the
preamble bit sequence, only a reasonable sequence of control steps needs
to be defined for establishing a synchronization and optimization procedure
on the basis of a handshake mechanism, which can be organized by
10 independent processors in the transmitting and the receiving systems units.

One possible handshake procedure works as follows. At the beginning of a
communication process, predefined values for the control parameters
— namely m , n and the optical power of the transmitters — are chosen, m
15 and n being known to the control processors of the transmitting system unit
and the receiving system unit as well. It is reasonable to start a
transmission of test signals at a low default data rate in order to realize
signals with a reasonable signal-to-noise ratio which allows for unmistakable
optimizing steps. As test signals, the preamble bit pattern of the first data
20 packet to be transmitted could be used. As a result of this first attempt to
start a communication process, the receiver, especially its bit position
estimator and its decoder, delivers a measure of the actual signal-to-noise
ratio and the bit error rate. Taking these data, the control processor of the
receiving system unit determines whether these data are between
25 predefined limits and whether there is room for improvement for the data
rate and/or the optical output power of the transmitter. The rules according
to which a new set of the adaptable control parameters is taken, can be
given by mathematical relations which might be determined experimentally
or by means of modelling calculations. In a reverse process, the control
30 processor of the transmitting unit expects information about possible
improvements being transmitted from the receiving unit, and reacts with the
command for the continuation of the synchronization process using a new
set of values for the control parameters. If no response from the receiver

1 appears, the transmitting unit might make an attempt to establish communication by subsequently decreasing the transmission rate and thus improving the signal-to-noise ratio. This procedure stops either after having determined an optimized set of control parameters or after having found
5 that communication is impossible within the degrees of freedom of the system. If the communication is established once, the receiving unit can send a request for changing the control parameters whenever the signal-to-noise ratio changes, and the transmitting unit reacts accordingly.

10 A further degree of freedom for changing the data rate can be introduced by allowing for switching between different coding schemes. Starting from the PPM-based system described above and assuming a given pulse duration T_p and time frames with given duration T_2 , the data rate can be increased by adding additional pulses to each time frame, thus increasing the number of
15 bits which are related to a single time frame with T_2/T_p possible pulse positions. Due to limitations of the average output power of the transmitting unit, the adding of additional pulses might require a reduction of the peak power. In order to realize this approach the PPM-based system described above must be modified. First, the preamble bit pattern of each packet must
20 include information about the coding scheme used. Second, the preamble processor 49 must be modified for being enabled to handle the preamble. Furthermore, the information about the proper coding scheme must be forwarded to the decoder 56 whose function must depend on the coding scheme. The same holds for the bit position estimator if its content is used
25 for the estimation of the signal-to-noise ratio and/or the bit error rate.

In conclusion, based on analyses of the data throughput, a method and an apparatus for wireless optical communication with adaptive data rates and/or levels of optical output power is proposed which allows for
30 optimizing the data throughput for a particular distance and ambient light environment. In accordance with the present invention full network connectivity within a prescribed range (e.g. 10 x 10 m) can be maintained at the expense of (often temporarily) reduced throughput. A low data rate,

1 e.g. 0.01 Mbps, may still be sufficient for connecting peripheral devices
such as printers 22, modems, keyboards 21 etc. to remote units 20, 23, 24,
25, as illustrated in Figures 1A and 1B. In addition, obstructions of the
propagation path (for instance by a person obscuring the photodiode of a
5 receiver) can be taken into account by transient resorting to a lower data
rate if necessary. Experiments have shown that a person standing 30 cm
away from a receiver can cause a 5 dB to 7 dB optical power drop (tilted
transmitter/receiver configuration located at desktop level in opposite
corners of a 10m x 10m room). While full network connectivity is
10 maintained due to the present invention even in 'normal' adverse
conditions, the user may only notice a graceful degradation in throughput
instead of an abrupt communication cutoff.

When employing the present invention in an IR network with repeater which
15 retransmits correctly received data packets, as illustrated in Figure 1D, the
overall network throughput can be increased. Alternatively, one or several
participating units (stations) may be configured to retransmit packets not
addressed to themselves. As an example (see Figure 5), a packet
transmitted from a transceiver of a first unit at 0.1 Mbps can reach the
20 transceiver of another unit - exposed to direct sunlight - and being
separated some 7 - 10 meters from the first unit, resulting in a throughput
of $\simeq 1$ %. With a repeater station inbetween, the full 10 Mbps rate can be
maintained resulting in a throughput of $\simeq 50$ % (packet transmitted twice).
The repeater concept is also suited to increase the overall network range
25 which is important in large offices, for example.

1 CLAIMS

Claims

- 5 1. A wireless optical communication system for data transmission with at least one transmitting unit (70; 75) for radiating modulated optical signals and at least one receiving unit (71; 76) for receiving said optical signals, characterized by control means (72; 77, 78) for dynamically adapting the optical output power of said transmitting unit (70; 75) and/or the data rate of
10 said data transmission according to given rules such that said receiving unit's (71; 76) error rate does not exceed a predefined upper limit.
- 15 2. The communication system of claim 1, wherein the control means (72) comprises at least one processor which receives information about the error rate of the data transmission and/or the signal-to-noise ratio from the receiving unit (71) for adjusting the optical output power of the transmitting unit (70) or the data rate of the transmission according to predefined rules.
- 20 3. The communication system of claim 1 or 2, wherein the receiving unit (71) comprises a transmitter for optical signals and the transmitting unit (70) comprises a receiver for optical signals for exchanging information about the optical output power of the transmitting unit (70) and/or the data rate of the transmission with the control means (72) via wireless optical
25 communication.
- 30 4. The communication system of claim 1, wherein the control means comprises at least two processors, one (77) being part of the transmitting unit (75) and one (78) being part of the receiving unit (76), both communicating with each other for setting the optical output power of the transmitting unit (75) and/or the data rate of the transmission in an interactive process according to given rules.

1 5. The communication system of claim 4, wherein the processors (77, 78) communicate via bidirectional wireless optical communication.

5 6. The communication system of claim 3 or 5, wherein the receiver for optical radiation comprises

- a detector (34) for optical radiation which converts optical signals to electrical signals;
- an amplifier (35, 45) and a bandpass filter (46) for said electrical
10 signals;
- a signal averager (47, 50, 51, 52, 54.1 -54.x) which periodically samples incoming electrical signals during a time frame of a predefined duration T_1 and superposes said sampled signals of subsequent time frames m times, where m is a predefined integer, and
- 15 • a decoding system (55, 56) for the extraction of the data from the signals after being processed by the signal averager.

7. The communication system of claim 6, wherein the data rate is adapted by modifying the time per pulse T_p in combination with the corresponding
20 modification of the electrical bandwidth B of the receiver in accordance with $B \simeq \frac{1}{T_p}$.

8. The communication system of claim 6 or 7, wherein the data are split into subsets which are transmitted with k subsequent repetitions, where k is a
25 predefined integer ≥ 1 and each subset has a predefined duration T_2 .

9. The communication system of claim 8, wherein

- the data rate is adapted by changing the number k of said repetitions
30 according to predefined rules, and
- the signal averager and the decoding system are synchronized to the transmission of the packets, i. e. $T_1 \geq T_2$ and $k = m$.

1 10. The communication system of claim 9, wherein

- each subset carries n bits which are coded by pulse position modulation (PPM) within the duration T_2 ,
- 5 • the receivers comprise means for decoding PPM-coded data.

11. The communication system of claim 10, wherein the data rate is adapted by changing n in combination with an adjustment of the optical power of the transmitting unit (70, 75).

10

12. The communication system of any of the preceding claims, wherein the control means comprise at least one optical detector, which is used for determining the intensity of ambient light.

15 13. Method for wireless optical data communication between at least one transmitting unit (70; 75) and at least one receiving unit (71; 76), comprising the steps of

- radiating optical signals from said transmitting unit (70; 75);
- 20 • detecting said optical signals by the receiving unit (71; 76);
- adjusting the optical output power of said transmitting unit (70; 75) and/or the data rate of the transmission according to given rules such that said receiving unit's error rate does not exceed a predefined upper limit.

25

14. The method of claim 13, wherein the step of adjusting the optical output power and/or the data rate includes the steps of

- evaluating the error rate of the data transmission and/or the signal-to-noise ratio of the received signals and/or the intensity of ambient light for adjusting the optical power and/or the data rate;
- 30 • providing commands concerning said adjustment to the transmitting unit and the receiving unit;

- 1 • processing said commands by the transmitting unit and the receiving unit for initializing the adjustment of the optical power and/or the data rate.

5 15. The method of claim 14, wherein the commands are provided to the transmitting unit and the receiving unit by means of wireless optical communication.

10 16. The method of any of the claims 13 - 15, comprising the steps of

- converting the detected optical signals to electrical signal;
- amplifying and filtering said electrical signals;
- sampling said electrical signals during a time frame of predefined duration T₁;
- 15 • averaging said sampled signals related to m subsequent time frames, m being an integer, and
- decoding said electrical signals.

20 17. The method of claim 16, wherein the step of adapting the data rate comprises the step of modifying the time per pulse T_p in combination with changing the bandwidth B of the receiver in accordance with $B \simeq \frac{1}{T_p}$.

25 18. The method of claim 16 or 17, wherein the data transmission is based on the steps of splitting up the data in subsets of duration T₂ and transmitting each subset with k subsequent repetitions, k being ≥ 1.

19. The method of claim 18, comprising the steps of

- 30 • adapting the data rate by changing the number k of the repetitions according to predefined rules,
- synchronizing the time frames for the sampling of signals with the subsets, and

- 1 • averaging the sampled signals of m equivalent time frames, i. e. $k = m$.

20. The method of claim 19, wherein the data transmission comprises the coding of n bits, n being an integer, by pulse position modulation (PPM)
5 within each subset.

21. The method of claim 20, comprising the step of adapting the data rate by changing n in combination with an adjustment of the optical power of the transmitting unit.

10

22. A receiving unit for use in a wireless optical communication system in accordance with claim 1, comprising a receiver (71) for optical signals and means for exchanging information with the control means for dynamically adapting the data rate of the transmission and/or the optical output power of
15 the transmitting unit according to given rules such that said receiving unit's error rate does not exceed a predefined upper limit.

23. The receiving unit of claim 22, wherein the receiver (71) has the characteristics given in claim 6.

20

24. A receiving unit for use in a communication system in accordance with claim 4, comprising a receiver (76) for optical signals and a processor which communicates with a processor being part of the transmitting unit for setting the optical output power of the transmitting unit and/or the data rate in an
25 interactive process according to given rules.

25. The receiving unit of claim 24, wherein the receiver (76) has the characteristics given in claim 6.

30

1 / 8

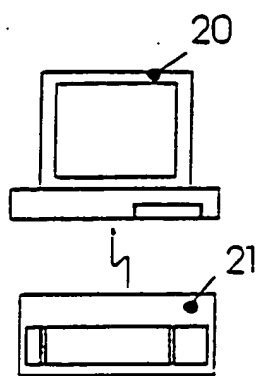


FIG. 1A

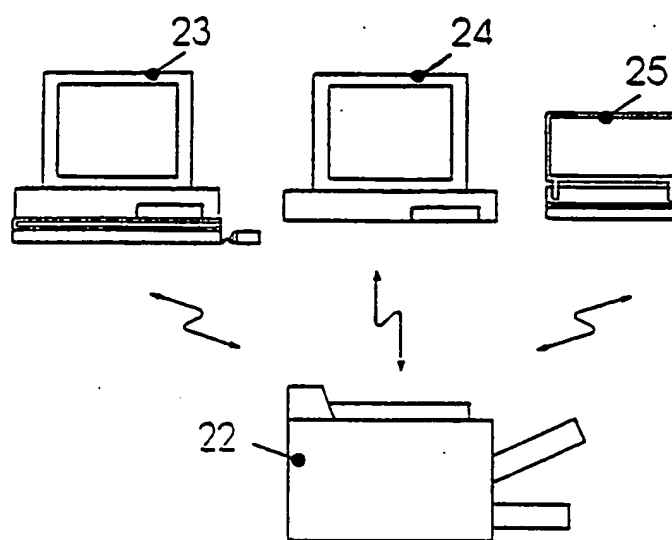


FIG. 1B

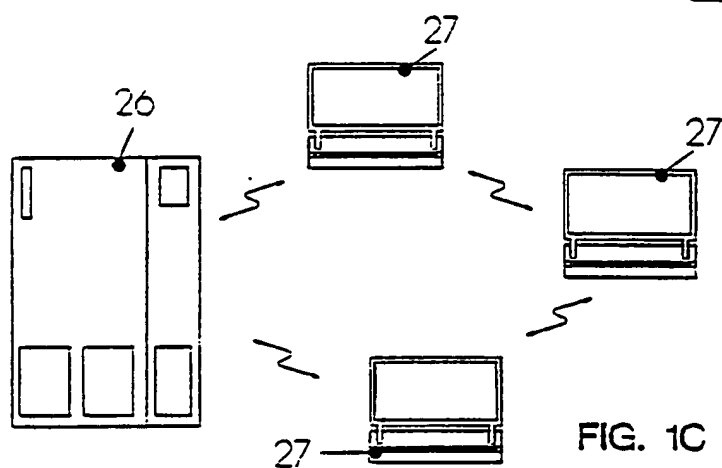


FIG. 1C

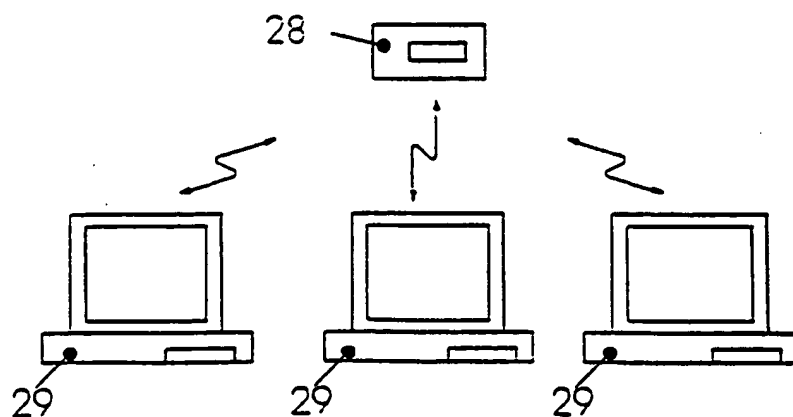


FIG. 1D

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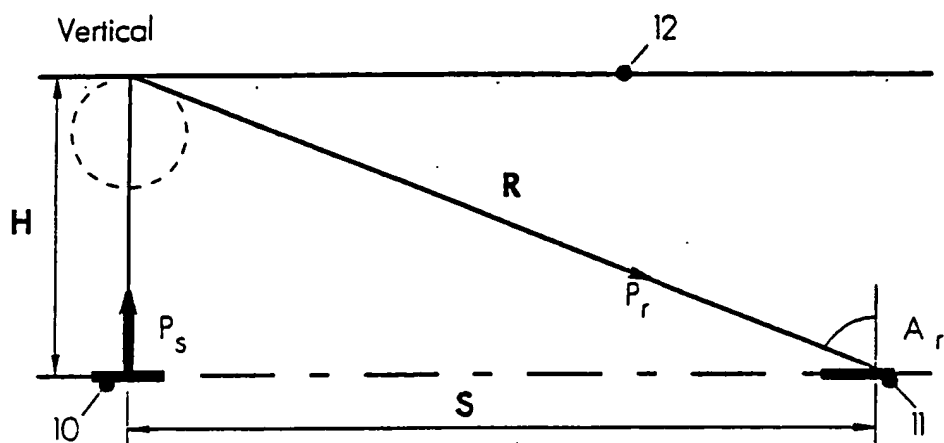


FIG. 2A

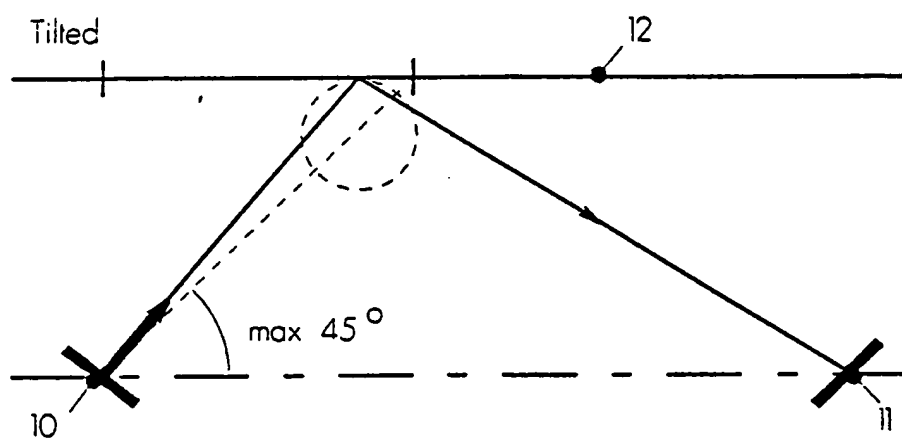


FIG. 2B

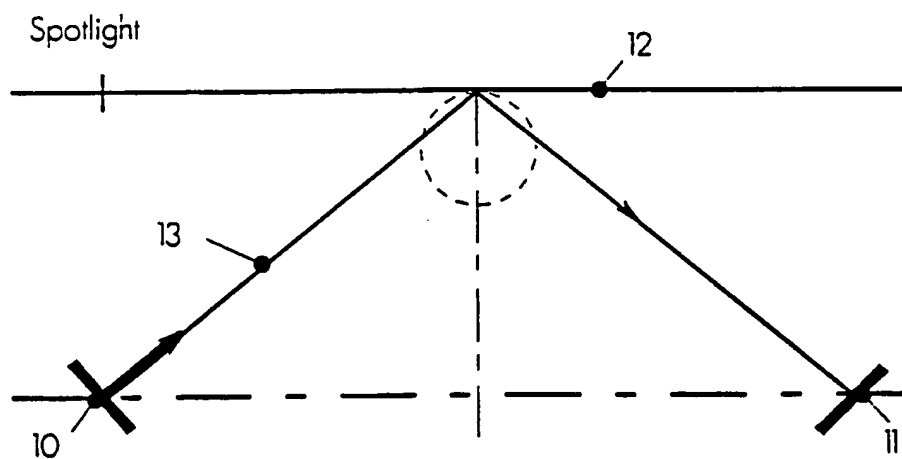


FIG. 2C

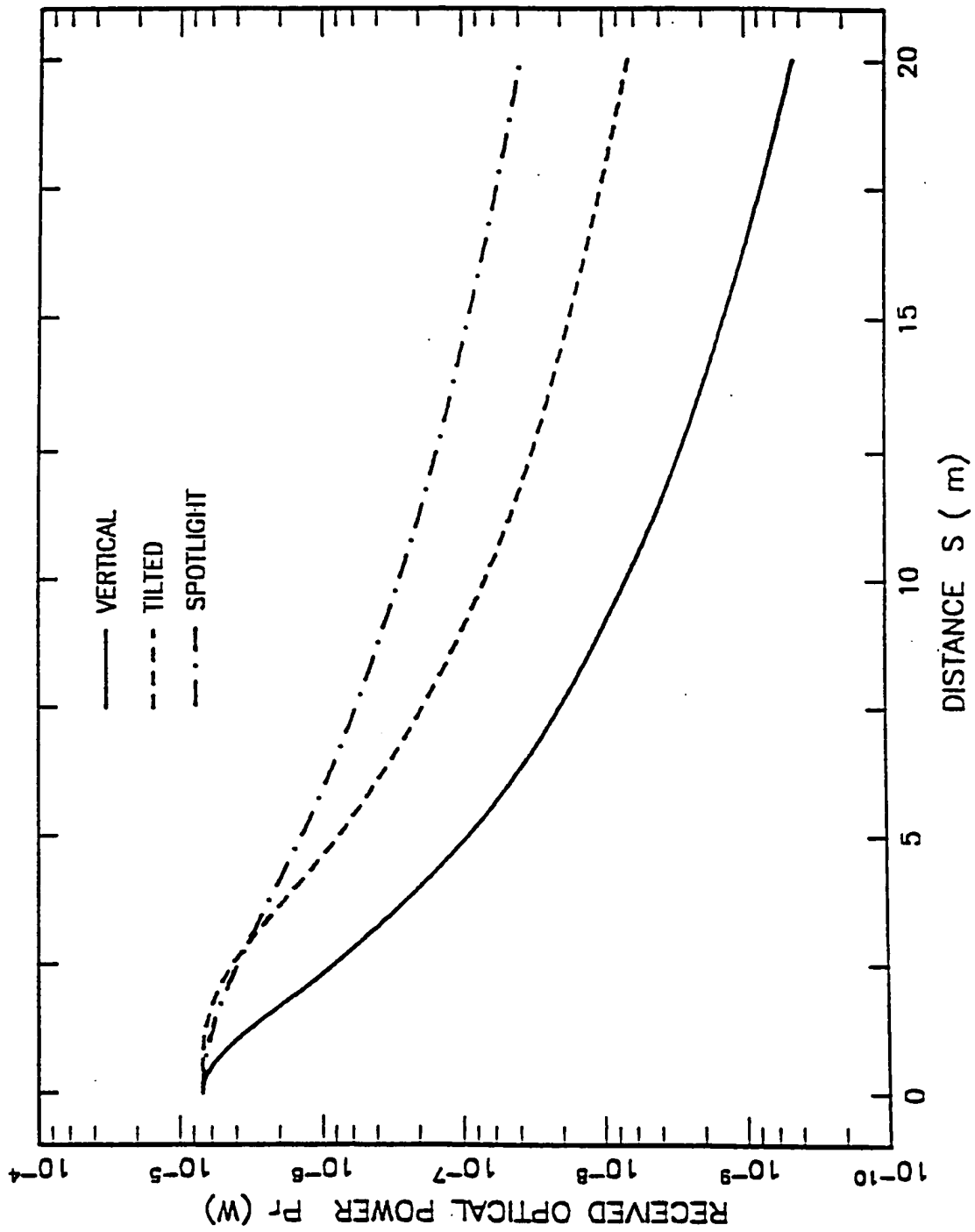


FIG. 3

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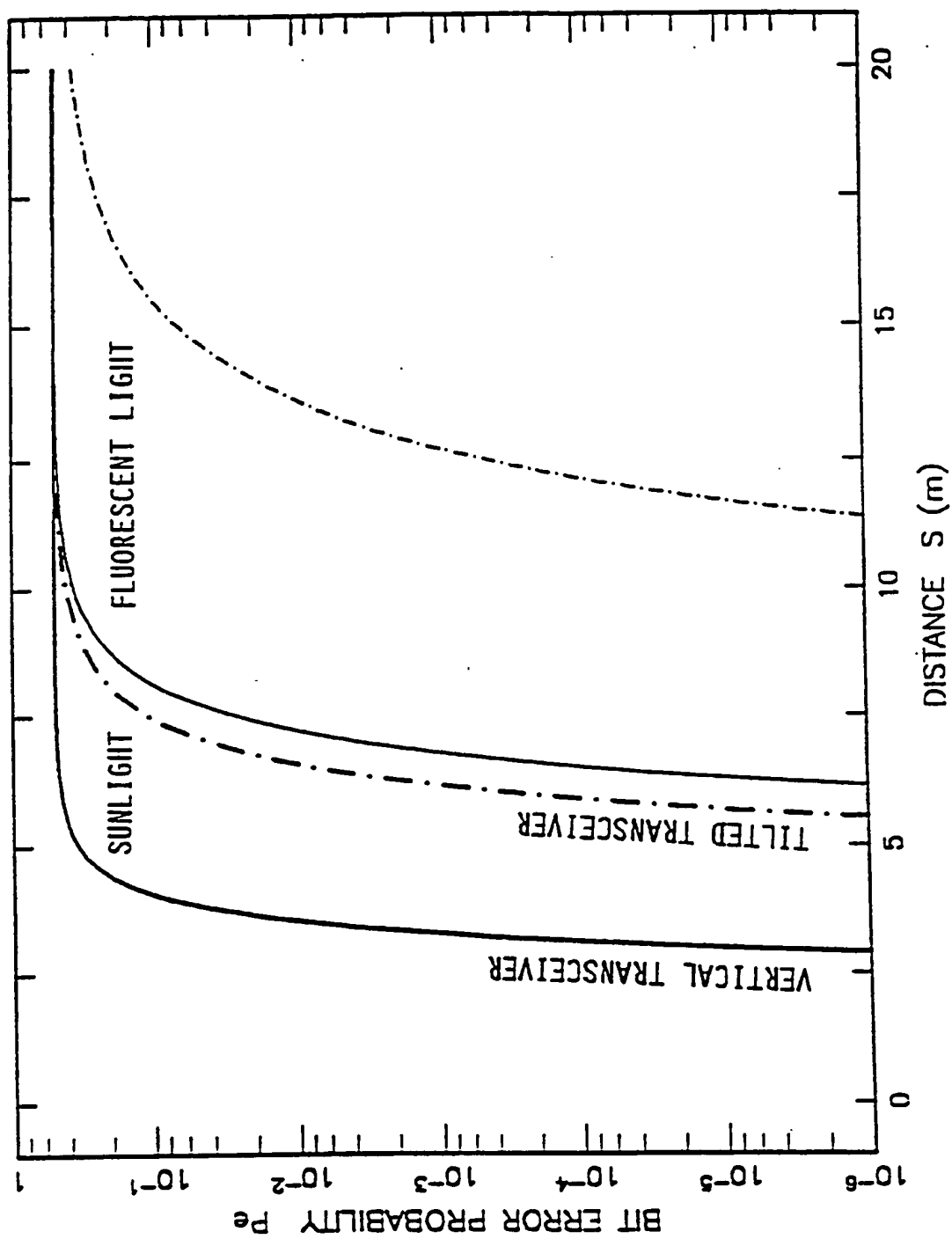


FIG. 4

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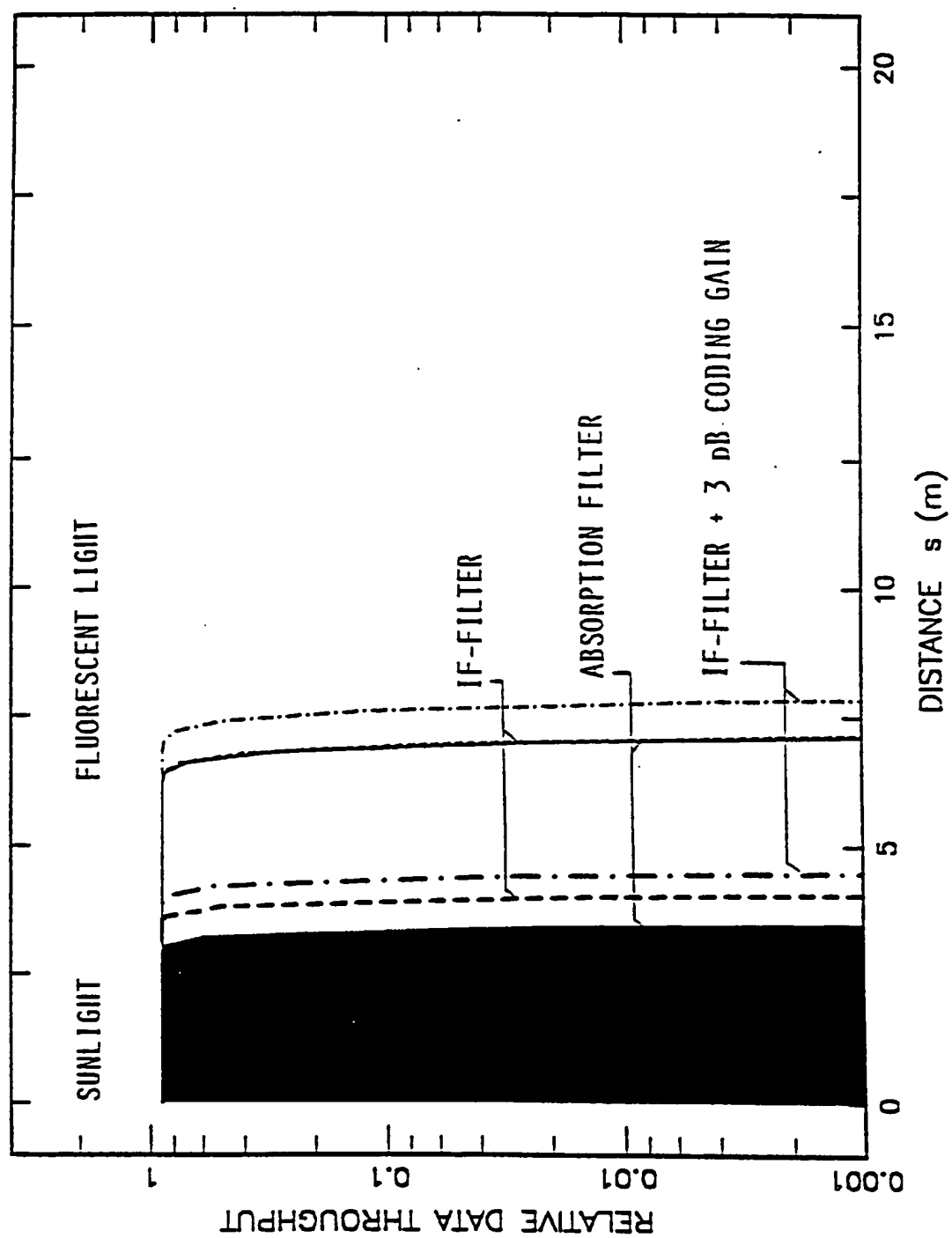


Fig. 5

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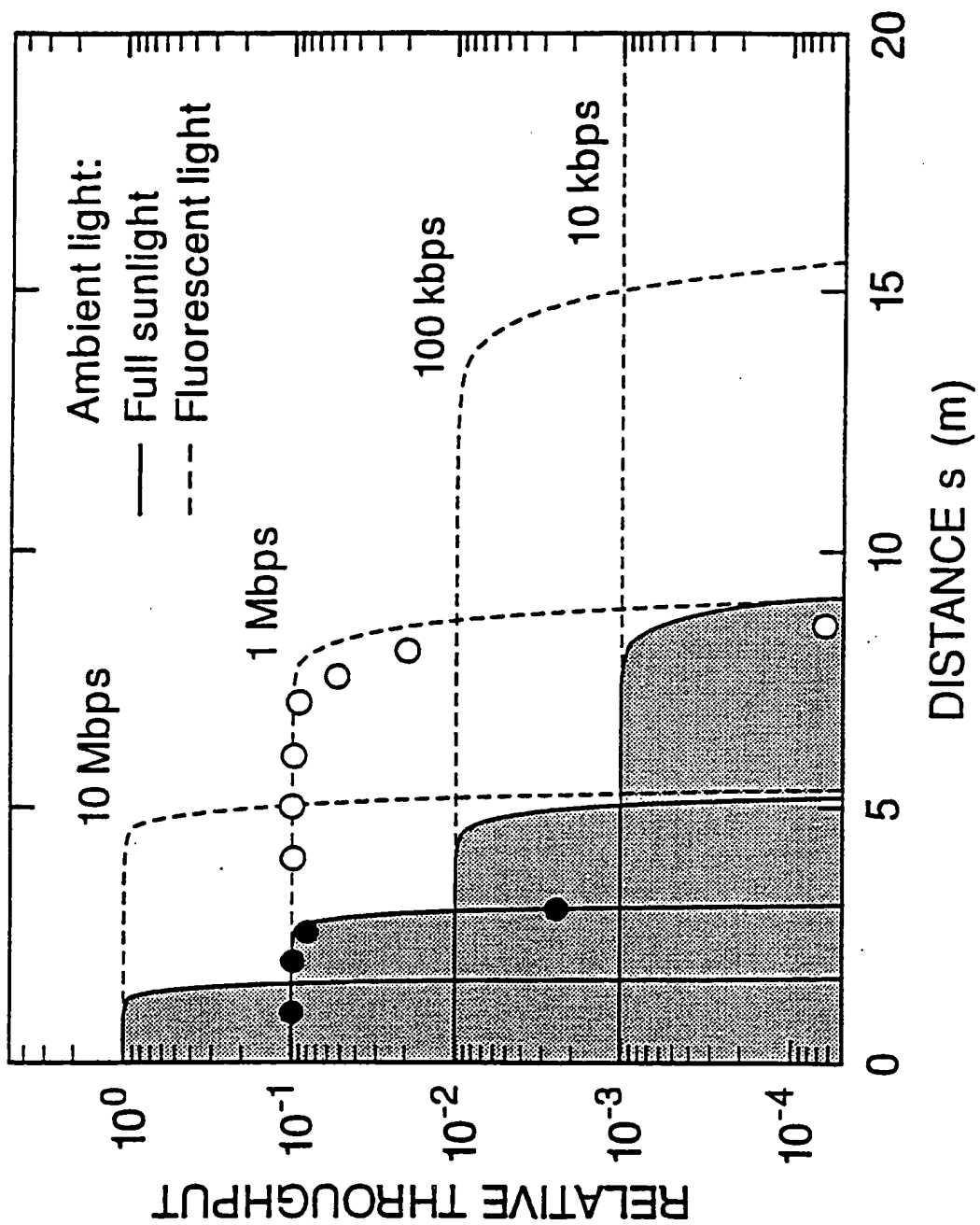


Fig. 6

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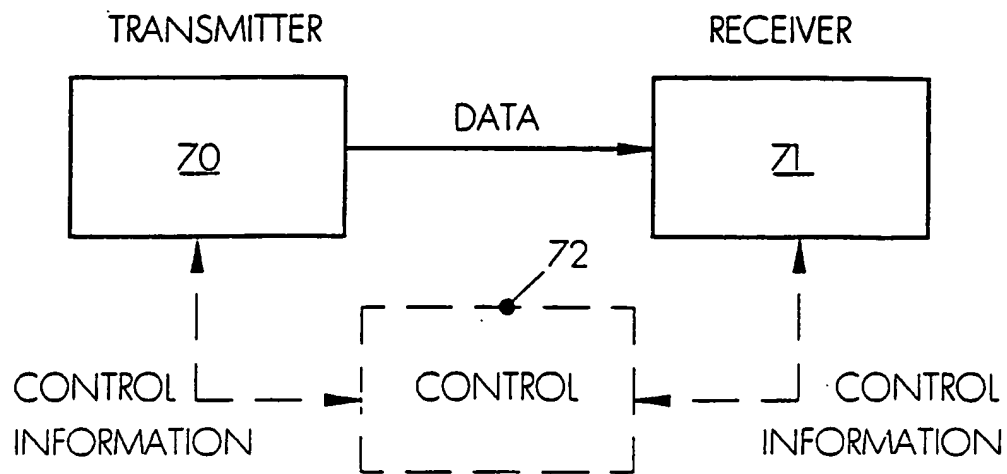


FIG. 7A

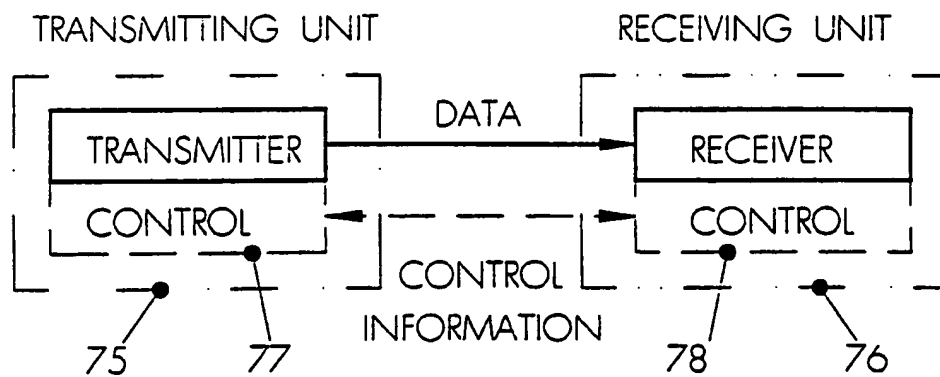


FIG. 7B

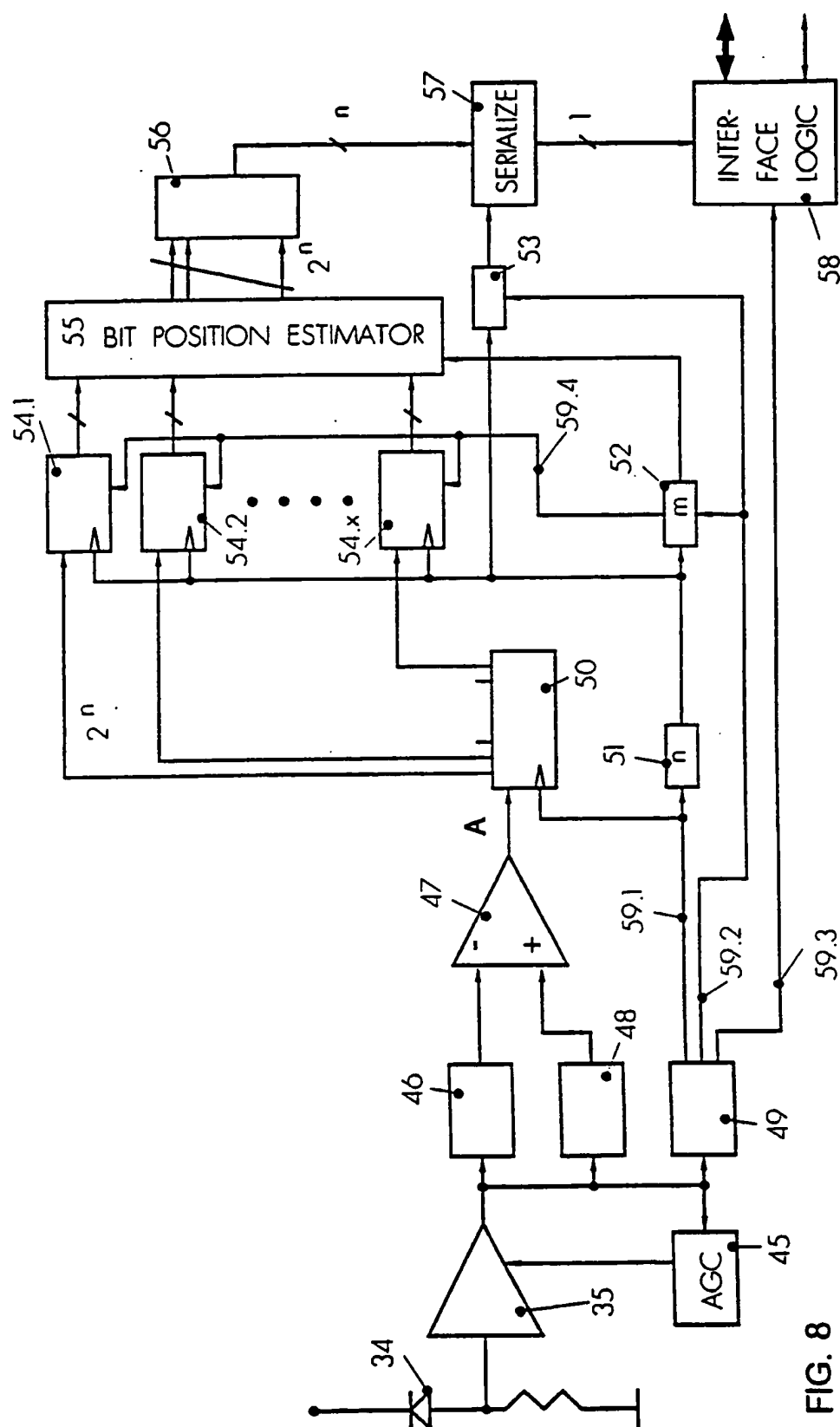


FIG. 8

INTERNATIONAL SEARCH REPORT

International Application No

PCT/EP 94/01196

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04B10/10

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 H04B G08C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 14, no. 200 (E-920) 24 April 1990 & JP,A,02 042 833 (SHARP) 13 February 1990 see abstract	1,2,13
A		6-11, 16-21, 23,25
X	--- PATENT ABSTRACTS OF JAPAN vol. 17, no. 559 (E-1445) 7 October 1993 & JP,A,05 160 792 (HAMAMATSU PHOTONICS) 25 June 1993 see abstract	1,2,13
A		6-11, 16-21, 23,25
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Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

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- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- "&" document member of the same patent family

Date of the actual completion of the international search

22 November 1994

Date of mailing of the international search report

13.12.94

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 94/01196

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 17, no. 35 (E-1310) 22 January 1993 & JP,A,04 256 234 (CANON) 10 September 1992 see abstract	1,4,13, 14,22,24
A	---	2,3,5,15
X	PATENT ABSTRACTS OF JAPAN vol. 17, no. 535 (E-1439) 27 September 1993 & JP,A,05 145 975 (CANON) 11 June 1993 see abstract -----	1,12-14